Characteristic Features of the Volcanism of the Siberian Platform

V. S. SOBOLEV[1]

WIDESPREAD VOLCANISM is characteristic of the Siberian platform, and was especially intense during uppermost Paleozoic and lower Mesozoic time. The Siberian traps, which occupy an area of more than 1,500,000 km^2, are best developed there. These are effusive and hypabyssal rocks of basalt-dolerite type, closely resembling trap rocks in other parts of the globe, especially the Karroo dolerites of South Africa.

The rise of trap magma began in the upper Paleozoic (Permian or even as early as Upper Carboniferous) time, and reached its climax in the Lower Triassic period. It was accompanied by the ejection of much pyroclastic material, which formed a thick series of tuffs. Lava sheets and hypabyssal intrusions of various kinds and sizes were formed.

The process of volcanism was rather complicated, and at present M. L. Lurie and V. Z. Masaitis distinguish five volcanic phases and 13 separate intrusive complexes, each having its own specific features and pattern of development in various parts of the platform. In spite of this, however, the magma had some characteristic features over the entire area, notably an iron content somewhat higher than is usual and an especially rapid increase of relative iron content during the process of crystallization differentiation. The increase of the iron content of the femic minerals in the process of crystallization prevails over the conventional reaction series of Bowen. For example, olivine of early formation contains about 20% fayalite, that characteristic of the usual type of traps contains about 40% fayalite, and the iron content of olivine in pegmatoid veins is as high as 80%.

The residue of the differentiation is as a rule micropegmatite, either in the mesostasis, or in some cases forming veinlets of granite composition. However, such veinlets are quantitatively very small. Much rarer is the formation of alkaline rocks, such as teschenite, in the last stages of differentiation.

The above characteristics of crystallization differentiation (rapid change of the iron content of femic minerals and the subordinate role of the discontinuous reaction series) are typical not only of the trap formations, but also of the deeper-seated magmatic complexes of the platform. The gabbro-anorthosite-granite complex of the margin of the Russian platform, with its characteristic granites of Rapakivi type, belongs to this group. These characteristic features distinguish complexes of this type from the typical granodiorite complexes of orogenic zones, in which crystallization largely corresponds to the well-known Bowen series. Relative increase of the iron content of femic minerals is there much slower, as is clearly seen by comparing it with the change in plagioclase composition.

Along with the trap formation, in part simultaneously and in part a little later, another type of volcanism developed widely on the margin of the platform, with the formation of ultrabasic and alkaline rocks. Differentiated effusive and intrusive complexes were formed in some regions, kimberlites in others.

A typical example of the differentiated complexes can be seen in the northern part of the Siberian platform in the area of the so-called Gulinski intrusion. The effusives range from meimechite, the closest extrusive analogue of true intrusive ultrabasite, to different kinds of alkaline basaltoids containing nepheline and plagioclase. Among the intrusives are all kinds of rocks from dunite to various alkaline rocks rich in nepheline. Carbonatite is also present. E. L. Butakova (1956) and Y. M. Sheinman (1955) have shown that the volcanic rock formation here was largely simultaneous with erup-

[1]Siberian Division, Academy of Sciences, Novosibizsk, U.S.S.R.

Manuscript received April 19, 1962.

tion of the trap magma. There are traps both older and younger than the alkaline rocks.

Kimberlite has been formed extensively in the northeastern border of the platform, more than 100 pipes and dikes being known there at present. For some kimberlite bodies the same sort of relationship to the traps has been established as for the alkaline basaltoids. Some of the kimberlite is not younger than Permian in age, since pyrope and diamonds from it occur in the Upper Permian deposits. However, there undoubtedly are younger kimberlites also, for a fragment of a belemnite of Upper Jurassic or Lower Cretaceous age was found in one of the pipes.

Kimberlite, as a magmatic rock, belongs to the ultrabasic group, its composition ranging from a form nearly devoid of alumina and alkalies to one rather high in Al_2O_3 and especially high in K_2O in mica-rich varieties. The principal mineral is always olivine, containing up to 10% Fe_2SiO_4, and is present in at least two generations: large crystals, commonly partly resorbed, and small idiomorphic microphenocrysts. Phlogopite occurs in idiomorphic plates and ranges widely in quantity. It is unquestionably magmatic. Pseudomorphs of pyroxene microlites are sometimes seen in the vitreous matrix. The latter is always altered. In the northern regions fine-grained monticellite has been found in kimberlite for the first time, chiefly in dikes. Nepheline also is supposed to be present. Pyrope, and probably picroilmenite and chrome spinel, commonly belong to the first generation of phenocrysts. Perovskite is a later accessory.

As in South Africa, the kimberlite has a brecciated structure and is contaminated by fragments of various sorts of rocks. There are, on the one hand, typical pyroclastic rocks filling explosion pipes, and, on the other, magmatic breccias with various contents of xenoliths. Since the rocks have been altered (serpentinized and carbonatized), it is not always possible to prove the presence of magmatic cement.

The fragments of other rocks may be subdivided into:

1) Fragments of ultrabasites and eclogites whose origin is in some way connected with the origin of the kimberlite itself;

2) Fragments of rocks picked up by the magma from (a) the crystalline basement formations, and (b) the sedimentary cover.

Fragments of the first type include various ultrabasites—olivinites, peridotites, and others—often containing pyrope as well as typical eclogites. The discovery of diamond-bearing eclogites, resembling the well-known eclogite xenolith found by Bonney (1899) in South Africa, is of particular interest. Together with such eclogites brought up from great depth, there are eclogites and eclogite-like rocks (containing plagioclase) picked up from the crystalline basement and formed by eclogitization of hypersthene schists.

The fragments of rocks picked up by the magma vary widely in quantity and composition. Xenoliths of gneisses and schists are abundant in several of the pipes. This can be taken as proof that the "explosion" that formed the pipe took place at a level lower than the base of the sedimentary cover. Allowing for this, and taking into consideration the geophysical data on the depth of the crystalline basement in the area and also the thickness of the rocks since removed by erosion, we can say that the explosion took place at a depth somewhere between 2 and 4 km. The depth is greater than in the case of the formation of the trap necks, which was 0.5 to 1 km.

As in South Africa, xenoliths of rock formations that occur at much higher levels (sometimes several hundred meters higher) are found among the fragments, proving that there was not only an ascending but also a descending movement of the material in the pipe.

The synchroneity of their formation has led to the hypothesis of a genetic connection between the ultrabasic rocks and kimberlites and the trap magma of the Siberian platform. Petrographic data, however, do not support this hypothesis. The olivine of the kimberlites and the meimechites contains only 10% fayalite, and this is proof enough that these rocks could not have originated as a result of differentiation of the trap magma. The author quite agrees with Y. M. Sheinman's (1955) suggestion of the formation, in this case, of magmatic chambers at much deeper levels than those of the trap magma.

The development of trap volcanism on such an enormous scale leads us to the conclusion that regional melting of the basalt layer took place here, probably in its upper part. However, nowhere in the platform did the magma chambers reach the sialic shell, and the small granitoid veinlets were formed wholly as a result of local crystallization differentiation. Taking into consideration the existing data on the structure of the earth's crust in the platform, the depth of such magma chambers appears to have been about 25 km, and the geothermal gradient at the time of volcanism appears to have reached 40 C per kilometer.

Some differences in composition of the traps might have resulted from differences in depth of the magma chambers in different parts of the platform and resultant differences in the differentiation phenomena.

The presence of effusives of ultrabasic composition (meimechites, kimberlites) is definite proof of the existence of a corresponding magma. This magma could be formed only by the remelting of ultrabasic rocks, which in turn is proof of the existence of rocks of corresponding compositions below the Mohorovicic discontinuity.

In the case of the formation of differentiated complexes, there is no doubt of the presence of big magma chambers and a relatively slow rise of magma either to the earth's surface or to the corresponding intrusion chambers. A complicated evolution of the rocks takes place as a result of involvement of the higher levels of the earth's crust in melting and, perhaps, as a result of assimilation and differentiation.

In the case of the kimberlites the quantity of rising magma is very small. This can hardly be the result of the low penetrability of the earth's crust. Rather, it is a proof of the formation of very small magma chambers in which remelting was partial, and a magma which rose very rapidly up the deep fissures containing many suspended crystals that formed not only as a result of crystallization in the chamber but also that remained as a result of the partial melting.

Not only theoretical calculations but also experimental data now show that if diamonds were formed at a temperature of about 1200 C, the pressure must have been more than 40 kilobars. The notion that diamonds were brought by the magma from great depth, and not formed at the time of explosions near the earth's surface, can be considered valid. Sometimes, on the basis of the above data, an attempt is made to determine the depth of the magma chamber from the implied hydrostatic pressure of the overlying rocks. This approach we cannot agree with, since the pressure in the earth's crust, within the zone of metamorphism, can be as high as 15 kilobars, which is several times the pressure resulting from load at that depth, the difference between the pressure at the time of the mineral formation and the calculated pressure due to the load being as much as 10 kilobars. Such zones of higher pressure may extend into the depths of the mantle, and it is to them that the regions of kimberlite development are likely to have belonged. The depth of formation of the magma chambers, in this case, may be less than calculated—that is, not 150 km but 70 to 100 km. As a result, when magma rises to a higher level, pressure still remains high, though it falls by a quantity corresponding to the weight of the vertical column of magma. In places at a depth of 3–4 km (see above), a breaking of the earth's crust occurred, accompanied by the formation of peculiar pipes and a sudden pressure decrease, constituting a kind of explosion. A great quantity of pyroclastic and xenogenic material rushed into the pipe, part of it being thrown up and then sucked back into the pipe again. The fragments filling the pipe may later be cemented by the rising magma.

The pressure before the explosion is not only below that shown by the equilibrium curve of diamonds but also below that shown by the curve of pyrope, since the kelyphite rims around grains of the latter must have formed before the explosion. The fact that the diamonds are neither completely resorbed nor graphitized is due to the rapid rise of the magma and its comparatively low temperature. The temperature of the magma must be lower than that shown by a curve corresponding to the region of metastable existence of diamonds (V. Sobolev, 1960), which begins at 1200 C at normal surface pressure and rises to 2200 C at 30 kilobars. As is known, the diamonds show only traces of graphitization, which appear as graphitic rosettes near some inclusions.

Recently, in connection with the discussion of the composition of the subcrustal substratum, great attention is once more being paid to the eclogite problem. The suggestion has been made (Fermor, 1914; Lovering, 1958) that the substratum below the Mohorovicic discontinuity is eclogite. Some authors are of the opinion that this eclogite layer extends to a depth of 900 km (V. V. Belousov, 1960), i.e., to the base of the Galitzin layer. The only valid data available for discussion of this matter have been derived from study of the kimberlites—a fact that makes it desirable to treat this problem here.

As is known, a great quantity of xenoliths of ultrabasic rocks, in some cases directly related to eclogites, are to be found in many kimberlite pipes. This fact suggests that such xenoliths are at least in part the remains of the partially-melted substratum, the more so as the composition of the olivine in them resembles that of the first-generation olivine of the kimberlites. The question is, however, still open to discussion. There is some probability that these rocks were picked up by the kimberlites during their rise toward the surface, not only in the substratum but also at much higher levels. The ultrabasic magma chambers are likely to have revived several times, and the formation of ultrabasite intrusions may have taken place during the first stages, further intrusions taking place later with the rapid movement of new portions of magma in new geologic conditions. Such intrusive massifs could have consisted of pyrope peridotite, such as that in Czechoslovakia.

The absence of diamonds (at least in appreciable quantity) in the ultrabasite xenoliths speaks against the supposition that the xenoliths were brought directly from the deep magma chamber. Although the presence of diamonds in pyrope peridotites has been asserted by some workers, neither a xenolith with a diamond, nor its photograph, nor a detailed description of it, can be found anywhere. Many attempts to obtain diamonds by grinding and concentration of considerable quantities of ultrabasite xenoliths and eclogites have resulted in failure. This fact, however, cannot altogether disprove the hypothesis of the subcrustal origin of these rocks, since the distribution of diamonds in the substratum may be nonuniform. Also, they may have, for the most part, crystallized directly with the formation of kimberlite magma.

On the other hand, two findings of diamond-bearing eclogites, which are subject to no doubt and have been described in detail, are proof of the existence of subcrustal eclogites. Diamond formation in the zone of metamorphism is impossible. The pressure there has never reached even that of coesite crystallization, which is lower than that of diamond formation. It is interesting to point out that the Jakutian diamond-bearing eclogite in its ratio of FeO to MgO is nearer to basic rocks than to ultrabasic rocks; it undoubtedly was not brought directly from the deep magma chamber, but was picked up from higher levels in the substratum.

Comparing all the above-mentioned data, we come to the following conclusions regarding the constitution of the upper mantle and its relationship to the earth's crust:

1. At comparatively small depths, probably less than 50–70 km, the subcrustal substratum is of peridotite composition, corresponding approximately to the composition of meimechite or kimberlite, the latter being a magmatic rock.

2. In the region of kimberlite distribution, higher than the peridotite layer but below the Mohorovicic discontinuity, the substratum is eclogite with chemical composition very near that of basalt.

3. Pressures in the zone of metamorphism can vary greatly at one and the same depth, reaching at least 15 kilobars but never 20–25 kilobars.

4. There is some reason to believe that higher pressures are characteristic of large parts of the earth's crust, especially the border of the platforms. Pressure higher than simple hydrostatic pressure is also characteristic of the upper part of the subcrustal substratum in these same areas (probably down to a depth of about 150–200 km).

5. Higher pressure persisted in certain zones through considerable periods of geologic time, as is proved by the finding of ancient eclogitized schist in kimberlite of both Upper Paleozoic and Mesozoic age.

Examining the above statements, we come to the conclusion that the hypothesis of a subcrustal eclogite layer (Fermor, 1914) has been confirmed, but only in part. The author quite agrees with the opinion of J. F. Lovering (1958), V. V. Belousov (1960*b*), and others, that a change of conditions (chiefly pressure, rather than temperature) leads to a shift of the Mohorovicic discontinuity, with the formation of eclogites at the expense of gabbroic rocks of the "basalt" layer. The total thickness of the basic layer, however, is probably not more than 30–50 km. Thus the eclogite layer is not to be found all over the globe, but only in the zones of higher pressure. In some cases, the basalt layer has been fully eclogitized and has entirely disappeared, and the sialic layer has come into direct contact with the Mohorovicic discontinuity. We can approach the problem of distribution of the subcrustal eclogite layer by comparing geophysical and geologic data: the distribution of kimberlite, the appearance of eclogite inclusions in effusives, and, partly, the distribution of rocks formed at high pressures in the zone of metamorphism, such as kyanite schists, eclogites, jadeite (taking into consideration possible changes over periods of time).

In the zones of normal or lower than normal pressure, the pressure of about 15 kilobars, which is necessary for the formation of eclogites, is reached at a depth of about 60 km, which is, as a rule, below the boundary separating the basic and ultrabasic rocks. Garnet peridotites, or some interlayers of eclogites that are close to ultrabasic rocks in composition, may be present there. In such cases the Mohorovicic discontinuity evidently corresponds to the true compositional border between the basalt and the peridotite layers, not to a phase transformation.

The isobar of the limit of possible diamond formation (40 kilobars) is, of course, well below that level. In the areas of normal or lower pressures, it must be below 120 km. In the author's opinion, the penetration of magma from such a depth is unlikely. Still less likely is the preservation of the diamond, even if magma chambers have formed at such depths.

In connection with this problem it is interesting to compare the data on the finding of diamonds in meteorites. As far as is known, diamonds have been discovered in stone meteorites of ureilite type (first in the Novourei meteorite) and in some iron meteorites. The author quite agrees with the opinion of Urey (1954, 1957) that the presence of diamonds there is evidence of the formation of these meteorites by the breakdown of some celestial body, as big as the moon or bigger, in which the pressure was high enough for the formation of diamonds. Thus, we cannot agree with A. P. Vinogradov's (1959) opinion that achondrites were formed by the breakdown of small celestial bodies. The paragenetic associations characteristic of eclogites, and specifically pyrope itself, have not been found in the meteorites, however. This shows that in the basalt shell of the disintegrated body pressures nowhere reached 15 kilobars. This fact, together with the absence of meteorites of granitic composition, suggests that the body probably was smaller than the earth and less differentiated. This agrees with ideas which have already been developed on other grounds by A. N. Zavaritski (1943). The above-mentioned data do not, however, prove that all meteorites have had the same origin and resulted from the breakdown of one planet.

Various meteorites are still being searched for diamonds. This search is certainly of great interest, but there is little likelihood that diamonds will be found in other types of meteorites, particularly in chondrites. Without going into details on the hypotheses of the formation of chondrites, we are quite certain that in the later stages of existence of these meteorites the temperature was high enough so that diamonds would have turned into graphite even if they had existed. If, however, we should succeed in finding pseudomorphs of diamonds in chondrites, as we have in some iron meteorites, this would be a direct proof of the formation of chondrites by the breakdown of some big celestial body.

On the other hand, the discovery of graphite pseudomorphs of diamonds in iron meteorites shows that, after the breakdown of the parent planet, the temperatures of the meteorites were greater than 1200 C. The preservation of diamonds in the Canyon Diablo octahedrite suggests that the temperature of that meteorite at the time of the breakdown was below 1200 C, which means that it was not melted.

The general questions discussed here are, of course, still open to argument. Already, however, on the basis of available petrographic and mineralogic data, we can be more certain of the thermodynamic conditions in and the constitution of the upper mantle of the earth, and of the conditions of meteorite formation. The formation and alteration of diamonds are of particular importance in these considerations. There is no doubt that further mineralogic investigations in general, and the investigation of diamonds in particular, will open new approaches to the study of the composition of the earth and aid in penetrating the secrets of the solar system.

REFERENCES

BELOUSOV, V. V. 1960*a*. Development of the earth and tectonics. Sovetskaja Geologia 7.

——— 1960*b*. Development of the earth and tectogenesis. J. Geophysical Res. 65:4127–4146.

BOBRIEVICH, A. P., M. N. BONDAZENKO, et al. 1959. Diamond deposits in Yakutiya. U.S.S.R., Min. Geol. i Okhrany Nedv., Moscow. 527 pp.

——— G. J. SMIRNOV, and V. S. SOBOLEV. 1959. Eclogite xenoliths with diamond. Doklady Akad. Nauk., U.S.S.R.: 126(3).

BONNEY, T. G. 1899. The parent-rock of the diamond in South Africa. Roy. Soc. London Proc. 65:235–236.

BUTAKOVA, E. L. 1956. On petrology of ultrabasic and alkalic rocks of Meimecha-Kotuockii complex. Tr. Niga 86:6.

FERMOR, L. L. 1914. The relationship of isostasv, earthquakes, and volcanicity to the earth's infraplutonic shell. Geol. Mag. 51:65–67.

LEBEDEV, A. P. 1957. Some problems of the petrology of original diamond rock in U.S.S.R. Akad. Nauk., U.S.S.R., Izvestiya, ser. Geol. 11.

LOVERING, J. F. 1958. The nature of the Mohorovicic discontinuity. Am. Geoph. Union Tr. 39:947–955.

SHEINMAN, Y. M. 1955. Some petrologic characteristics of ultrabasic rocks, and ultrabasic activity in platforms. Zapiski Vsesoyuznogo Mineralogicheskogo Obshchestva.

SOBOLEV, V. S. 1936. Petrology of traps in the Siberian platform. Arctic Institute, Trans. 43: 224.

——— 1960*a*. Role of high pressure in metamorphism. Int. Geol. Cong., 21st Session, Rep. 1:14.

——— 1960*b*. Conditions of the formation of diamonds. Geol. and Geoph. 1.

UREY, H. C. 1954. Diamonds, meteorites, and origin of the solar system. Astroph. 129.

——— 1957. Diamonds in stone meteorites. Geochim. et Cosmochim. Acta 13:1–4.